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An Updated Nuclear Criticality Slide Rule

Functional Slide Rule

Prepared by
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Prepared for
U.S. Nuclear Regulatory Commission

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ABSTRACT

This Volume 2 contains the functional version of the updated nuclear criticality slide rule (more accurately, sliding graphs) that is referenced in *An Updated Nuclear Criticality Slide Rule: Technical Basis*, NUREG/CR-6504, Vol. 1 (ORNL/TM-13322/V1). This functional slide rule provides a readily usable "in-hand" method for estimating pertinent nuclear criticality accident information from sliding graphs, thereby permitting (1) the rapid estimation of pertinent criticality accident information without laborious or sophisticated calculations in a nuclear criticality emergency situation, (2) the appraisal of potential fission yields and external personnel radiation exposures for facility safety analyses, and (3) a technical basis for emergency preparedness and training programs at nonreactor nuclear facilities. The slide rule permits the estimation of neutron and gamma dose rates and integrated doses based upon estimated fission yields, distance from the fission source, and time-after criticality accidents for five different critical systems. Another sliding graph permits the estimation of critical solution fission yields based upon fissile material concentration, critical vessel geometry, and solution addition rate. Another graph provides neutron and gamma dose-reduction factors for water, steel, and concrete. Graphs from historic documents are provided as references for estimating critical parameters of various fissile material systems. Conversion factors for various English and metric units are provided for quick reference.

CONTENTS

Page

ABSTRACT . . . iii

LIST OF FIGURES . . . vi

ACKNOWLEDGMENTS . . . vii

1 INTRODUCTION . . . 1

2 EXPLANATION OF SLIDE RULE . . . 3
  2.1 SLIDES 1–5 . . . 3
  2.2 SLIDE 6 . . . 4
  2.3 CONVERSION FACTORS AND EQUALITIES . . . 5
  2.4 REFERENCE FIGURES . . . 5

3 SUMMARY/CONCLUSIONS . . . 21

4 REFERENCES . . . 23

5 APPENDIX . . . 25

LIST OF FIGURES

Figure		Page
1	Dose reduction factors for various shield thicknesses	6
2	LEU UO_2–H_2O critical sphere volume (L) vs uranium mass (kg)	7
3	LEU UO_2–H_2O critical sphere diameter (in.) vs uranium density (g/L)	8
4	LEU UO_2–H_2O critical sphere uranium mass (kg) vs uranium density (g/L)	9
5	LEU UO_2–H_2O critical infinite cylinder uranium linear density (kg/ft) vs diameter (in.)	10
6	LEU UO_2–H_2O critical infinite cylinder diameter (in.) vs uranium density (g/L)	11
7	LEU UO_2–H_2O critical infinite slab uranium areal density (kg/ft^2) vs thickness (in.)	12
8	LEU UO_2–H_2O critical infinite slab thickness (in.) vs uranium density (g/L)	13
9	HEU $UO_2(NO_3)_2$–H_2O critical sphere volume (L) vs uranium mass (kg)	14
10	HEU $UO_2(NO_3)_2$–H_2O critical sphere uranium mass (kg) vs uranium density (g/cm^3)	15
11	HEU $UO_2(NO_3)_2$–H_2O critical sphere diameter (in.) vs uranium density (g/cm^3)	16
12	HEU $UO_2(NO_3)_2$–H_2O critical infinite cylinder diameter (in.) vs uranium density (g/cm^3)	17
13	HEU $UO_2(NO_3)_2$–H_2O critical cylinder uranium linear density (kg/ft) vs diameter (in.)	18
14	HEU $UO_2(NO_3)_2$–H_2O critical slab uranium areal density (kg/ft^2) vs thickness (in.)	19
15	HEU $UO_2(NO_3)_2$–H_2O critical slab thickness (in.) vs uranium density (g/cm^3)	20

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1 INTRODUCTION

To perform safety analyses and to develop and maintain a program of emergency preparedness and response for nonreactor nuclear facilities that process fissile materials, it is necessary to hypothesize credible magnitudes of nuclear criticality accidents, potential personnel hazards, and safe corrective actions in the event of a nuclear criticality accident. In an effort to provide general technical information that relates to these requirements, this functional updated nuclear criticality slide rule (more accurately, sliding graphs) extends the capabilities of the original slide rule design[1] to include five different unreflected fissile material systems. Systems were selected for their potential relevance to U.S. Nuclear Regulatory Commission (NRC) licensed nuclear fuel cycle facilities fissile materials; that is,

1. Solution of $U(93.2)O_2(NO_3)_2$ @ $H/^{235}U = 500$
2. U(93.2) metal
3. Damp $U(93.2)_3O_8$ @ $H/^{235}U = 10$
4. Damp $U(4.95)O_2F_2$ @ $H/^{235}U = 410$
5. Damp $U(5)O_2$ @ $H/^{235}U = 200$

The purpose of the "slide rule" is to provide variably interrelated nuclear criticality accident information about the following:

- fission yield magnitude estimation (based upon personnel or field radiation measurements or various critical system parameter inputs);
- direct and indirect ("skyshine") prompt neutron- and gamma-radiation dose estimates at variable distances from the accident;
- time-integrated radiation dose estimates at variable distances from and time after the fission yield;
- fission-product, decay-gamma dose rates at variable distances from and time after the fission yield;
- 1-min fission-product, decay-gamma radiation dose integrals at variable distances from and time after the fission yield; and
- dose-reduction factors for variable thicknesses of steel, concrete, and water.

Reference graphs of shielding dose-reduction factors (Figure 1) and various critical systems (Figures 2−15) are provided. The functional slide rule is included in the Appendix to this Vol. 2 as six pages of sliding graphs (Slides 1−6), followed by some conversion factors and equalities. This information is provided within this brief document that is easily "hand-held" for (1) the rapid estimation of pertinent criticality accident information without laborious or sophisticated calculations in a nuclear criticality emergency situation, (2) the appraisal of potential fission yields and external personnel radiation exposures for facility safety analyses, and (3) the development of emergency preparedness and training programs at nonreactor nuclear facilities.

2 EXPLANATION OF SLIDE RULE

This revised slide rule includes 6 sliding graphs, Slides 1–6; 15 nonsliding graphs, Figures 1–15; and a list of conversion factors and equalities. Five sliding graphs, Slides 1–5, provide interrelated data for five different types of critical systems. One sliding graph, Slide 6, permits the estimation of first-pulse fission yields for high-enriched uranium [(HEU); i.e., 93 wt % ^{235}U in uranium] solutions and for low-enriched uranium [(LEU); i.e., 5 wt % ^{235}U in uranium] solutions and damp oxides. The list of conversion factors and equalities, as well as the nonsliding Figures 1–15, are provided for reference. Figure 1 provides neutron and gamma dose-reduction factors for various thicknesses of water, steel, and concrete shielding. Figures 2–15 provide low- and high-enriched uranium and water-critical parameters (i.e., mass, volume, uranium densities, sphere and infinitely long cylinder diameters, and infinite slab thicknesses, etc.) from an historic reference.[2]

As described in Vol. 1, Slides 1–5 were developed for bare critical systems having neutron- and gamma-leakage characteristics of the specified materials in the slide titles. Each of the two-dimensional (2-D) radiation-transport calculations were performed with the radiation sources located 1 m above the air-over-ground plane interface. The resulting doses and dose rates were calculated at various distances from the radiation source but also 1 m above the same air-over-ground plane interface. The intent of modeling the calculations in this manner was to simulate a criticality accident in an unshielded process environment that could be used to estimate the dose (rate) values to people at various distances from an accident.

As readily noticed, there is an abundance of mixed English and metric units used throughout the slide rule to accommodate historic and typical use in the U.S. industry. Historically, nonreactor nuclear facilities were built to English unit specifications (e.g., 50,000-gal tank, 16-in.-diam pipes/tubes, 2-gal/min pump capacity, etc.), whereas operating process specifications have evolved to metric units (e.g., grams of U or grams ^{235}U per liter of solution, kg U, grams of U per cubic centimeter, etc.). The unit of typical use is presented in the text, which is then followed by an alternative unit in parentheses. The intent of providing mixed units is to ease data conversion and manipulation during a potentially stressful period of emergency response when data exchange is provided in mixed units.

2.1 SLIDES 1–5

Though each of the Slides 1–5 is for a different system of fissile materials, the type of information presented is identical in each of the five slides. Each slide consists of five graphs. The bottom-right, vertical-logarithmic scale has an arrow pointer labeled "Fissions." The bottom-right graph is labeled "Estimated Fission Yield Based on Distant Gamma Dose Rate and Elapsed Time." The bottom-left graph is labeled "Estimated Prompt Doses Based on Total Fission Yield and Distance From Incident." The top-left graph is labeled "Integrated Total Dose (rads) Based on Estimated Fission Yield, Distance From Incident and Time." The top-right graph is labeled "Accumulated One-Minute Dose (rads) Based on Estimated Fission Yield, Distance from Incident and Time of Entry After Incident."

The estimation of dose, dose rate, and fission yield can be related in a "forward" or "backward" manner. That is to say in a forward manner, given a fission yield of some magnitude (e.g., 10^{17} fissions), as positioned on the bottom-right, vertical-logarithmic scale, using the bottom-left graph one can determine an unshielded distant prompt total neutron/gamma free-air rad dose at a given distance (e.g., 100 ft) to be about 3.5 rads (based on Slide 1). Likewise, for an indicated 10^{17} fissions an integrated 1-min fission-product-gamma radiation exposure to a rescue team arriving within 20 ft of the subcritical system, 15 min after the criticality occurred, can be estimated to be about 0.15 rads from the top-right graph. The estimated fission-product-gamma radiation dose rate at 100 ft from the position of the criticality, 20 min after the 10^{17} fissions, is estimated to be about 0.32 rad/h. In a backward manner using the bottom-right graph, given an unshielded 4 rad/h fission-product-gamma

radiation dose rate field measurement at 100 ft from the accident site, 20 min after the criticality accident occurred, the slide rule can be positioned to estimate the criticality yield to be about 1.2×10^{18} fissions. Likewise, positioning the top-left graph for an unshielded total integrated neutron/gamma free-in-air dose measurement of 200 rad at 50 ft for 100 min after the criticality permits an estimated criticality accident yield of about 1.6×10^{18} fissions. During the evolution of an emergency response (e.g., collection of radiation exposure data and field radiation dose-rate data) estimates of fission yields and radiation exposures may be improved.

As presented in the top-left graph for integrated total dose, the delayed gamma dose contributions are included beginning 1 s after the event. The prompt neutron and gamma contributions correspond to less than 1 µs after the event. No delayed neutron contribution nor contributions from delayed gammas between 1 µs and 1 s were included in the dose curves.

The skyshine values from the bottom-left graph provide the skyshine component of the "total," "gamma," and "neutron" radiation doses due to the atmospheric backscattering of an upwardly directed, 90° cone of radiation from the criticality accident. This information could be useful for criticality accidents that are laterally shielded (e.g., a criticality accident in a drum surrounded by equipment or other drums of nonfissioning material, thin-roofed−thick-walled facility, etc.). Additionally, the ratio of the "γ skyshine" values to total "gamma (γ)" values can provide an estimate of totally shielded radiation doses and dose rates provided on the remaining graphs.

It can be observed from the bottom-left graph that at less than 1000-ft distances from the criticality, the "t skyshine," the "n skyshine," and the "γ skyshine" components of the unshielded "total (t)," "gamma (γ)," and "neutron (n)" doses are between a factor of about 1/3000th at 1 ft to 1/15th at 1000 ft from the criticality event. Therefore, the predominant radiation exposure comes from the forward-penetrating radiation at the air-over-ground interface. Depending upon the location of exposed people and the effectiveness of intervening dose-reduction shielding, skyshine may or may not be a significant portion of a person’s radiation exposure. Likewise, other estimates from the slide rule would need to be tempered with an understanding of potential influences of intervening shielding and skyshine.

2.2 SLIDE 6

Slide 6 provides the "First Pulse Fission Yield Estimates for Vertical and Horizontal Cylinders of HEU and LEU Solutions" and oxides. Slide 6 also consists of five interrelated graphs. The mid-right, vertical-logarithmic scale has an arrow pointer labeled "Addition rate (gal/min)." The top-left graph provides the "Fission Yield" for a "LEU Vertical Cylinder Diameter (in.)" based upon the uranyl nitrate solution or uranium oxide uranium density (g U/L) and the solution or oxide addition rate. The top-right graph provides identical information for a "LEU Horizontal Cylinder Length (in.)." The bottom-left, 2-D graph provides the fission yield for a "HEU Vertical Cylinder Diameter (in.)" based upon a uranium solution density (g U/L) and the solution addition rate. The bottom-right graph provides identical information for a "HEU Horizontal Cylinder Length (in.)."

Slide 6 may also be used in a forward or backward manner: That is, based upon a solution addition rate, solution uranium density, cylinder dimension (diameter or length) and cylinder orientation (vertical or horizontal), a fission yield may be estimated. For example, given a 30-g HEU/L addition rate of 0.4 gal/min into a 26-in.-diam vertical cylinder provides a first-pulse fission yield of about 9×10^{16} fissions at a volume of approximately 23 gal of solution. Assuming that the given configuration will become subcritical at less than 23 gal of solution, if there is a 5-gal (i.e., 18.94-L) excess of solution, then, from the "Conversion Factors and Equalities" it will require approximately an additional (18.94 L)·(10^{17} fissions/L) or 1.9×10^{18} fissions to evaporate enough water to cause

the system to be subcritical. Alternatively, Slide 6 may be used in a backward manner by selecting a fission yield and examining the parameters resulting in that fission yield.

2.3 CONVERSION FACTORS AND EQUALITIES

The listing of conversion factors and equalities are provided for handy reference in the interpretation of field data or translation of the slide rule to field applications. Some guidance is provided, such as the number of fissions required to evaporate 1 L of room-temperature water and the number of fissions produced over a time period for a given volume of solution. Such rules-of-thumb are inherently approximate and may be influenced by complex mechanisms. However, the application of these rules-of-thumb should be accurate within about a factor of 2.

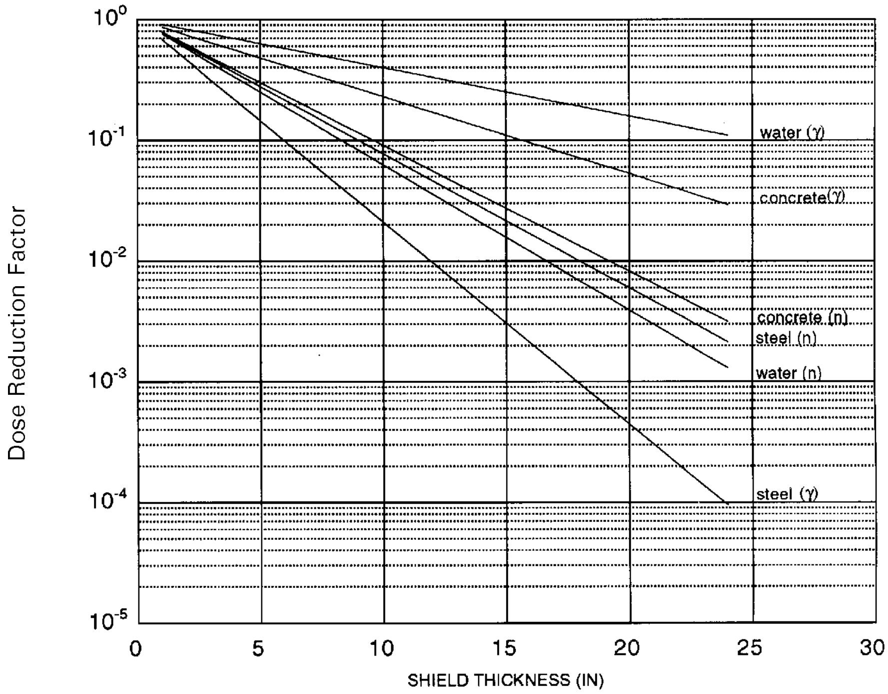
2.4 REFERENCE FIGURES

Figures 1 through 15 are provided as comparative references to potential systems of interest for emergency planning, preparedness, training, and response. They may be used for approximating the radiation dose reduction due to concrete, steel, and water (Figure 1) or for approximating the critical parameters of idealized water-reflected critical systems (Figures 2 through 15). The figures are not included for the purpose of precisely evaluating shielding and subcritical or critical systems. Precise nuclear criticality safety evaluations for normal and credible abnormal fissile material conditions should be performed by experienced nuclear criticality safety specialists who are familiar with computational evaluations and analyses of the normal and abnormal fissile material processes that will influence the approach to the critical state.

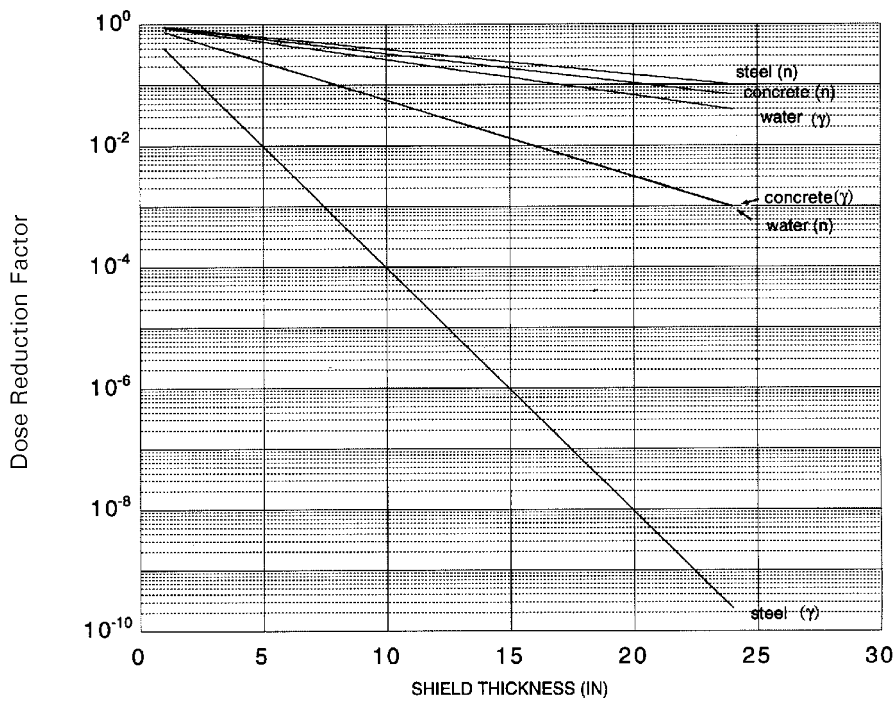
Figure 1a provides the effective prompt fission neutron- and gamma-radiation, dose-reduction factors for multiple layers of a specified shielding material located at 24-ft intervals from the criticality accident out to a distance of 240 ft. The thicknesses of the thin shielding materials considered were 1-in. (2.54-cm)-thick layers of steel, or 3-in. (7.62-cm)-thick layers of concrete, or 3-in. (7.62-cm)-thick layers of water. The purpose of evaluating multiple thin layers of shielding materials was to simulate the effects of walls and equipment that may be intervening between operating areas of a facility. Because the dose-reduction factors are based upon coupled neutron-gamma calculations the influence of neutron-capture gammas is included in the gamma-radiation, dose-reduction factor.

Figure 1b provides extrapolated prompt fission neutron and delayed fission-product gamma radiation dose reduction factors for thin single shields of material (i.e., steel, concrete, or water) located approximately 10 ft from the criticality accident. The shielding effectiveness differences from Figure 1a are due to the higher energy of the nearly first-collision neutrons on the shield and the lower-energy, delayed fission-product-gamma radiation not having a neutron-capture-gamma component.

Figures 2 through 15 provide approximate critical parameters for various fully water-reflected geometries (i.e., spheres, infinitely long cylinders, and slabs having infinite lateral dimensions) for water-moderated systems of low-enriched uranium (LEU – 2.5, 3, 4, 5, and 6 wt % ^{235}U in uranium) and high-enriched uranium (HEU – 93 wt % ^{235}U in uranium).



(a) prompt radiation dose-reduction factors for multiple thin shields



(b) prompt neutron and delayed gamma dose-reduction factors for single shields

Figure 1 Dose reduction factors for various shield thicknesses

III.B.9-6 ARH-600

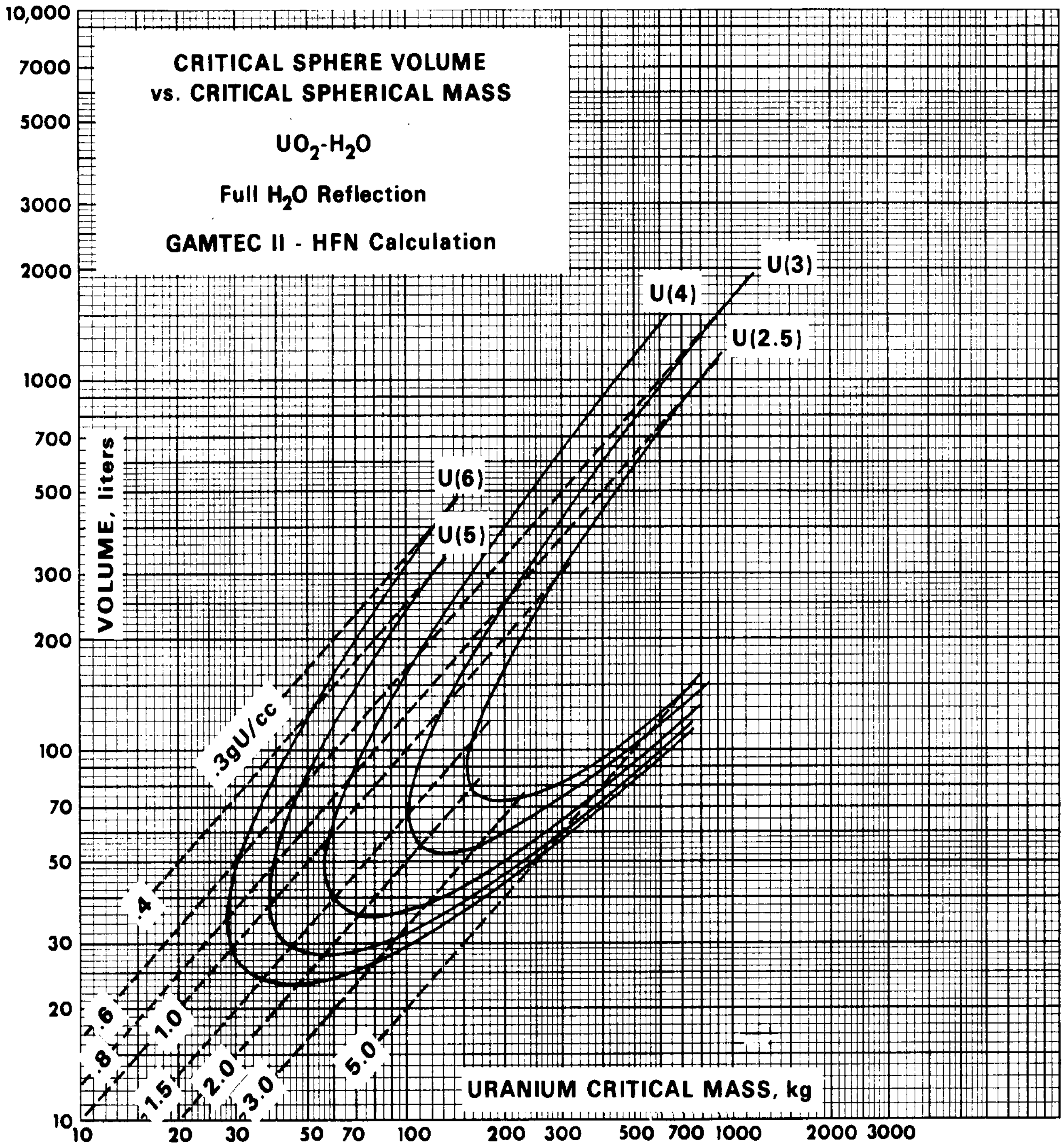


Figure 2 LEU UO_2–H_2O critical sphere volume (L) vs uranium mass (kg)

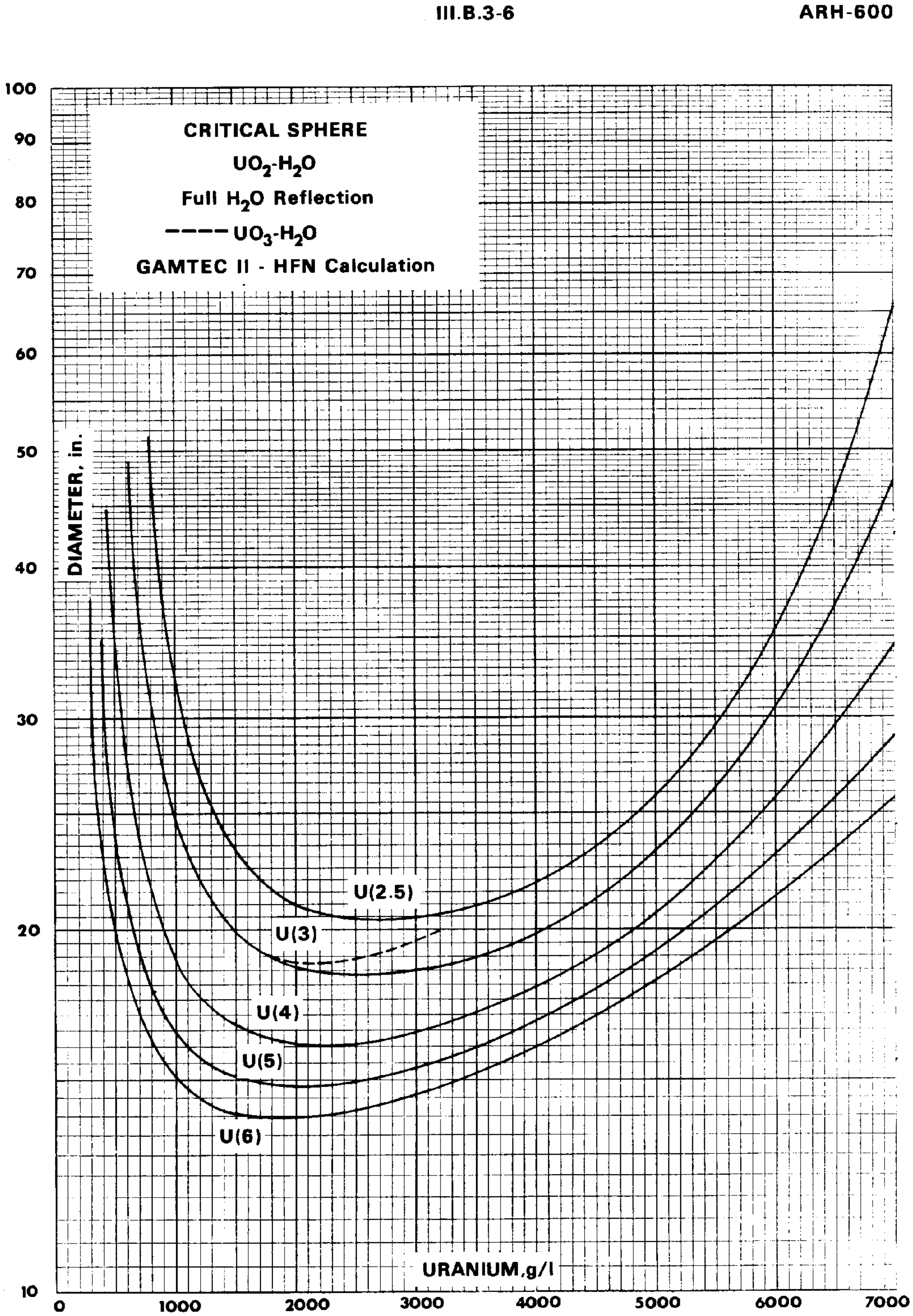


Figure 3 LEU UO_2–H_2O critical sphere diameter (in.) vs uranium density (g/L)

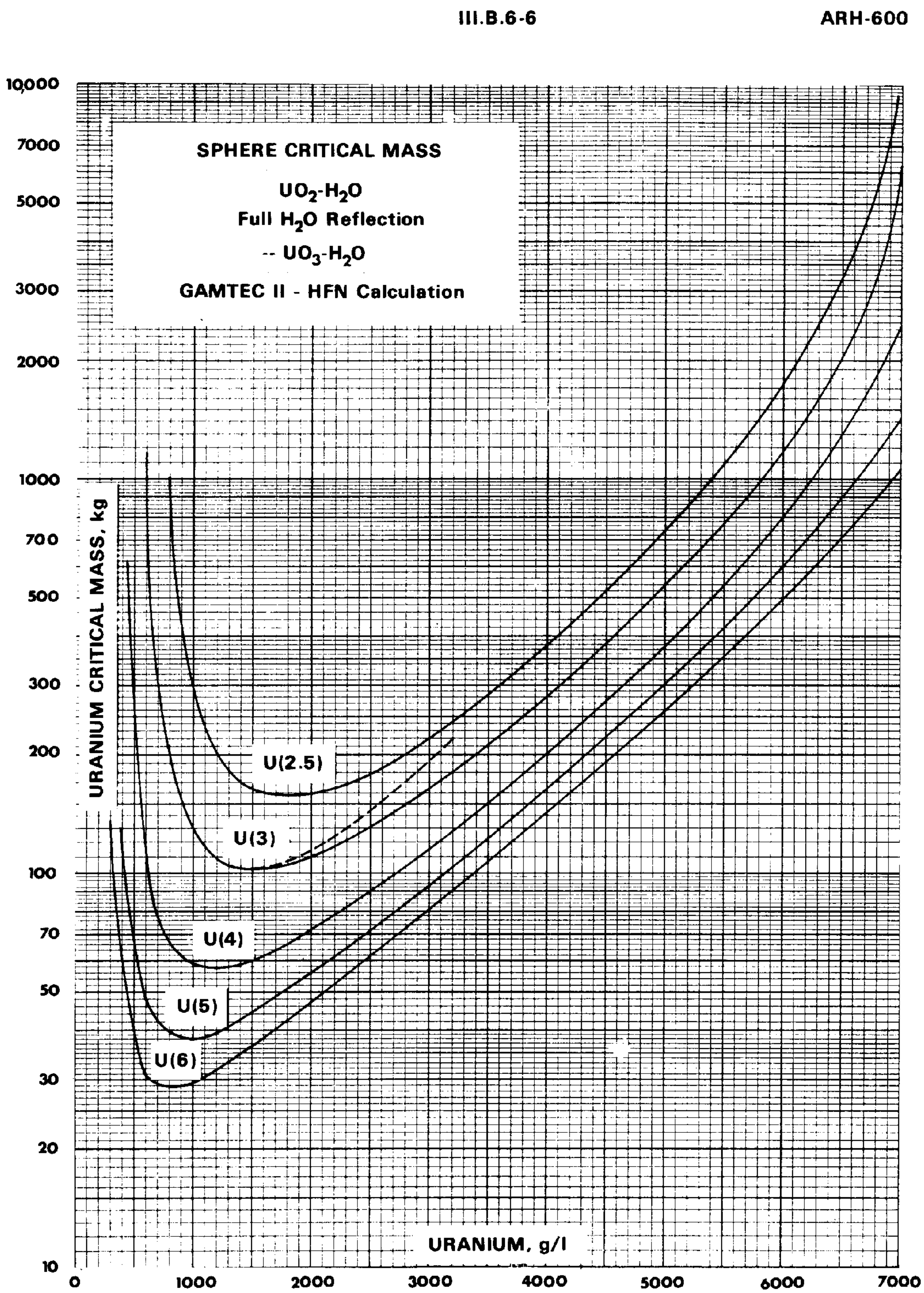


Figure 4 LEU UO_2–H_2O critical sphere uranium mass (kg) vs uranium density (g/L)

III.B.7-6 ARH-600

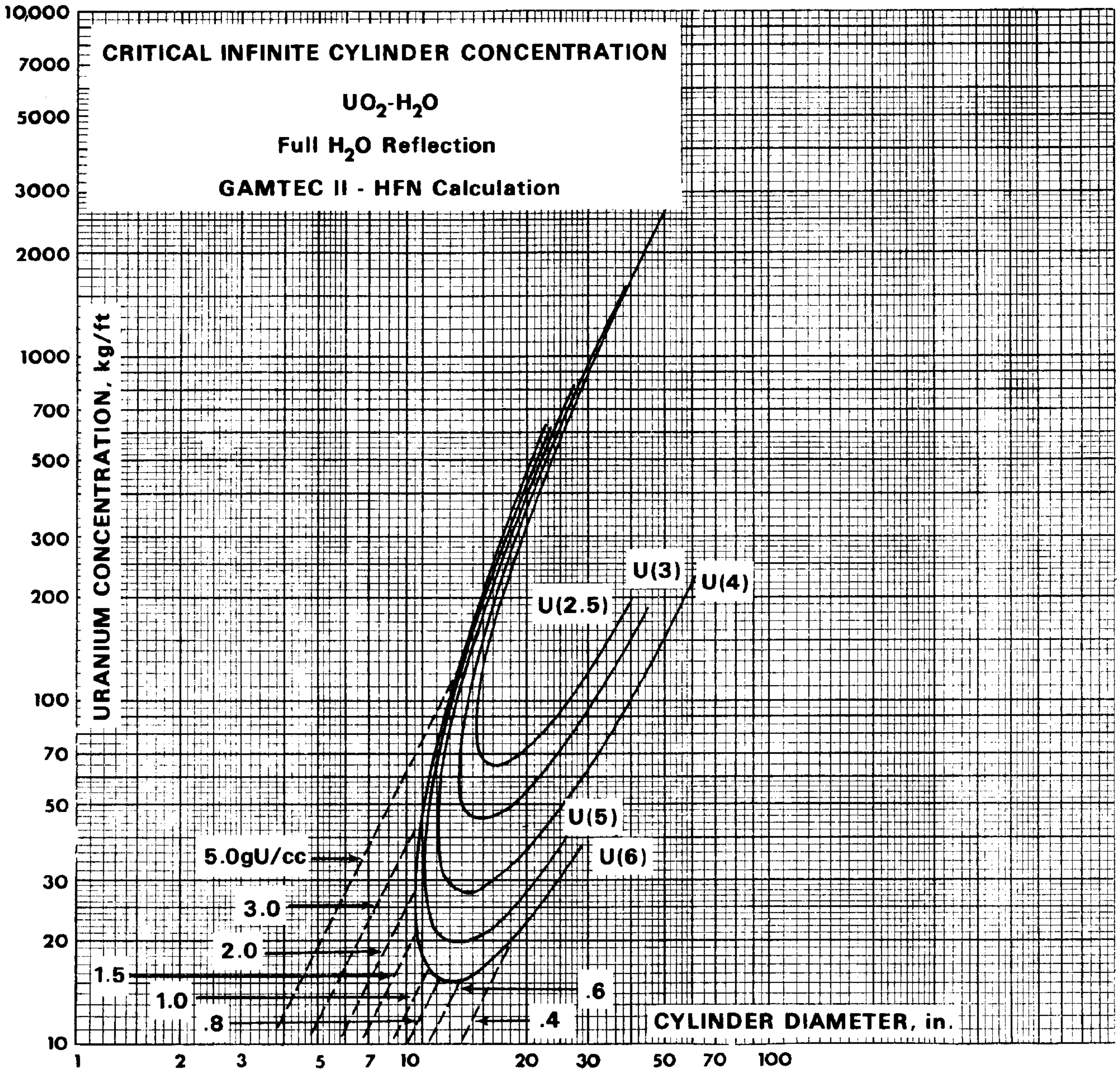


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Figure 5 LEU UO_2–H_2O critical infinite cylinder uranium linear density (kg/ft) vs diameter (in.)

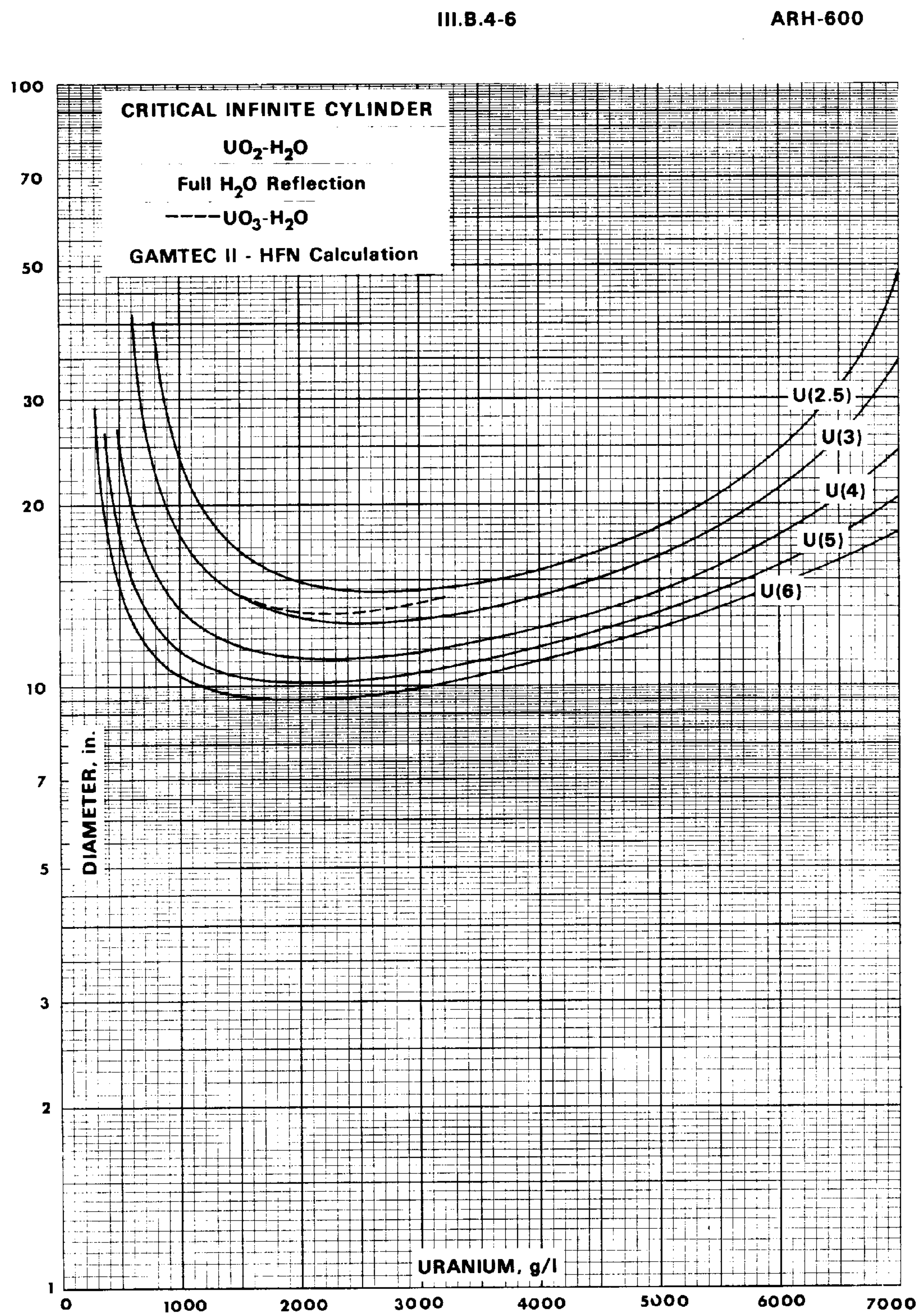

Figure 6 LEU UO_2–H_2O critical infinite cylinder diameter (in.) vs uranium density (g/L)

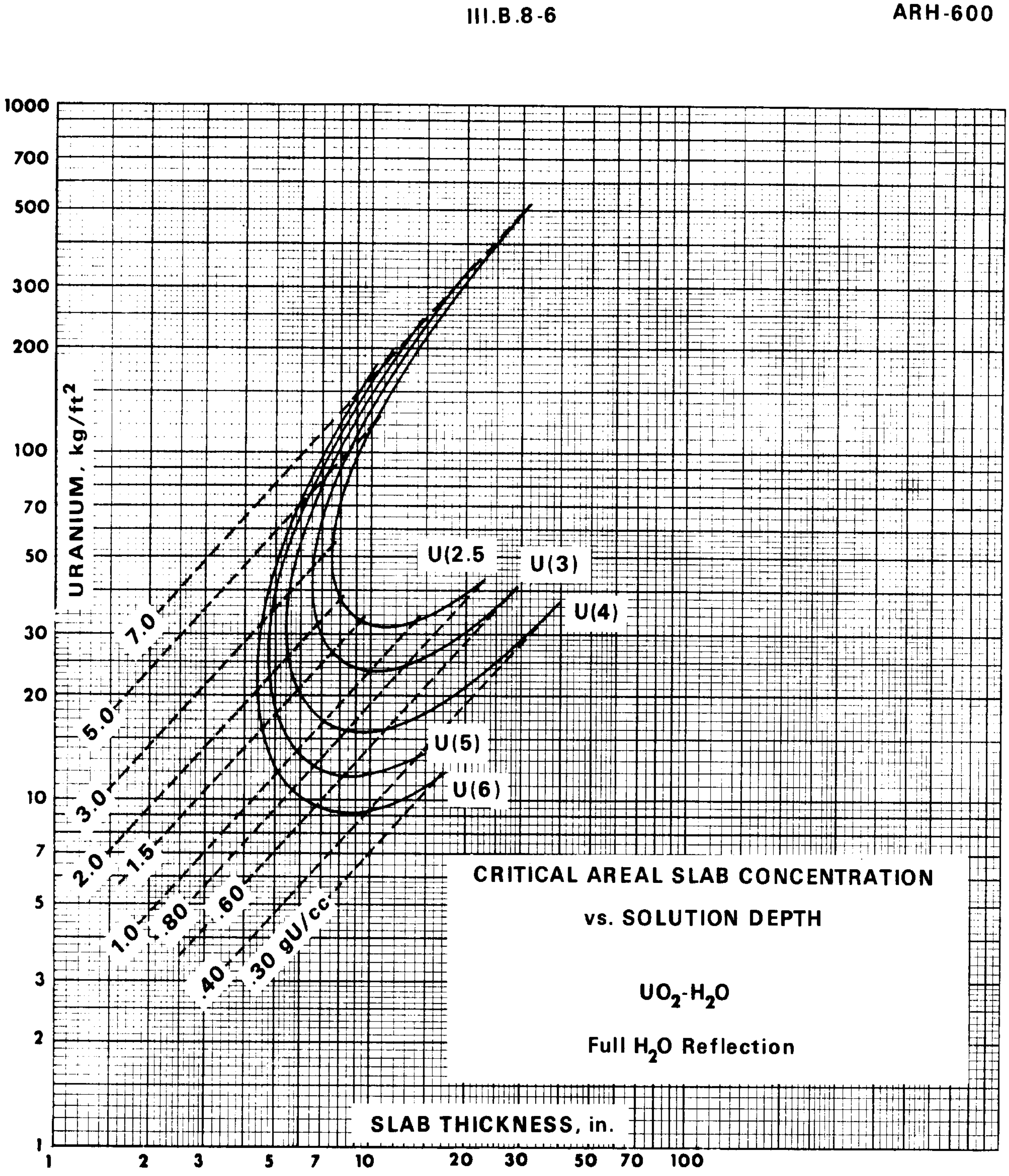

Figure 7 LEU UO_2–H_2O critical infinite slab uranium areal density (kg/ft^2) vs thickness (in.)

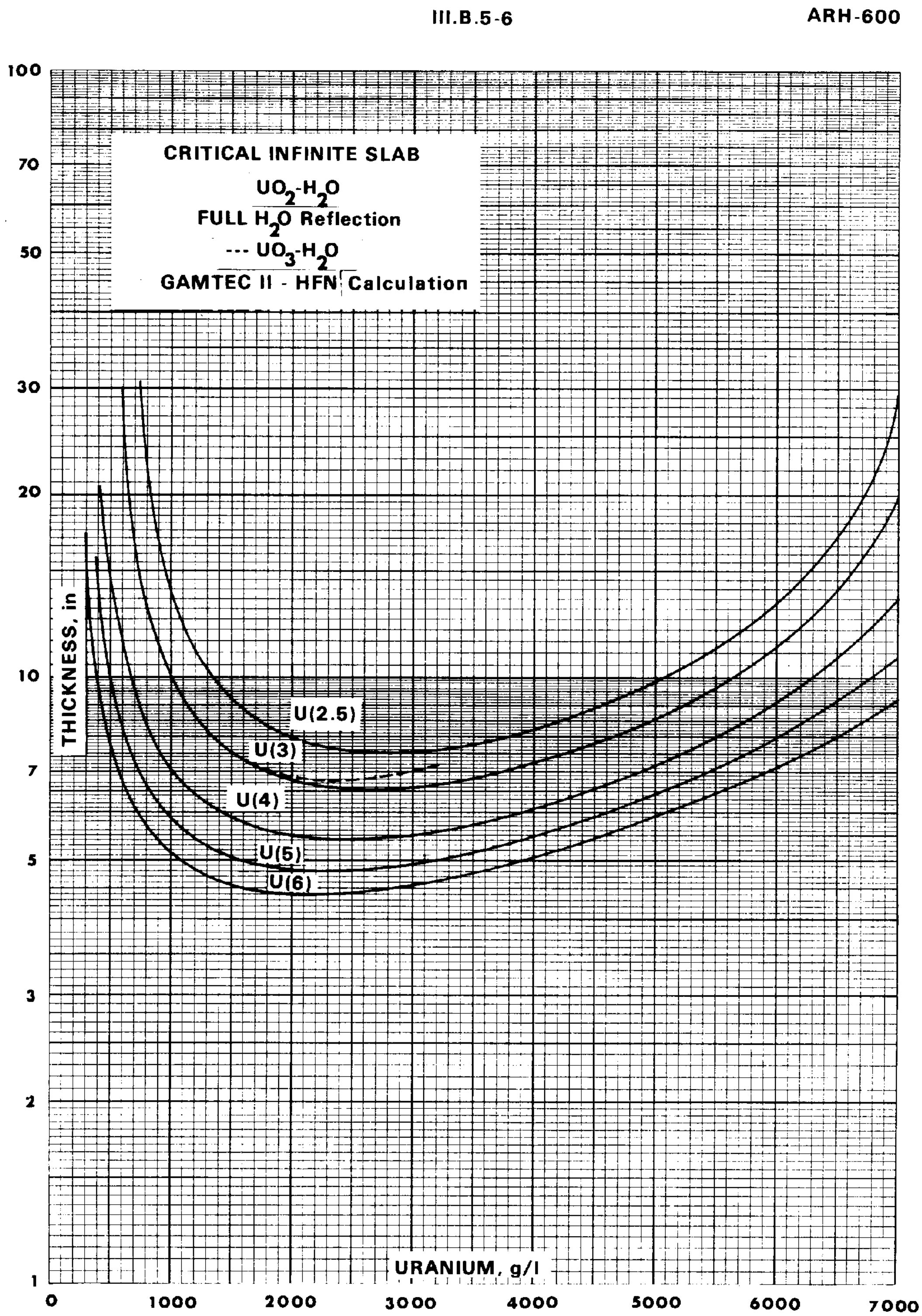

Figure 8 LEU UO_2–H_2O critical infinite slab thickness (in.) vs uranium density (g/L)

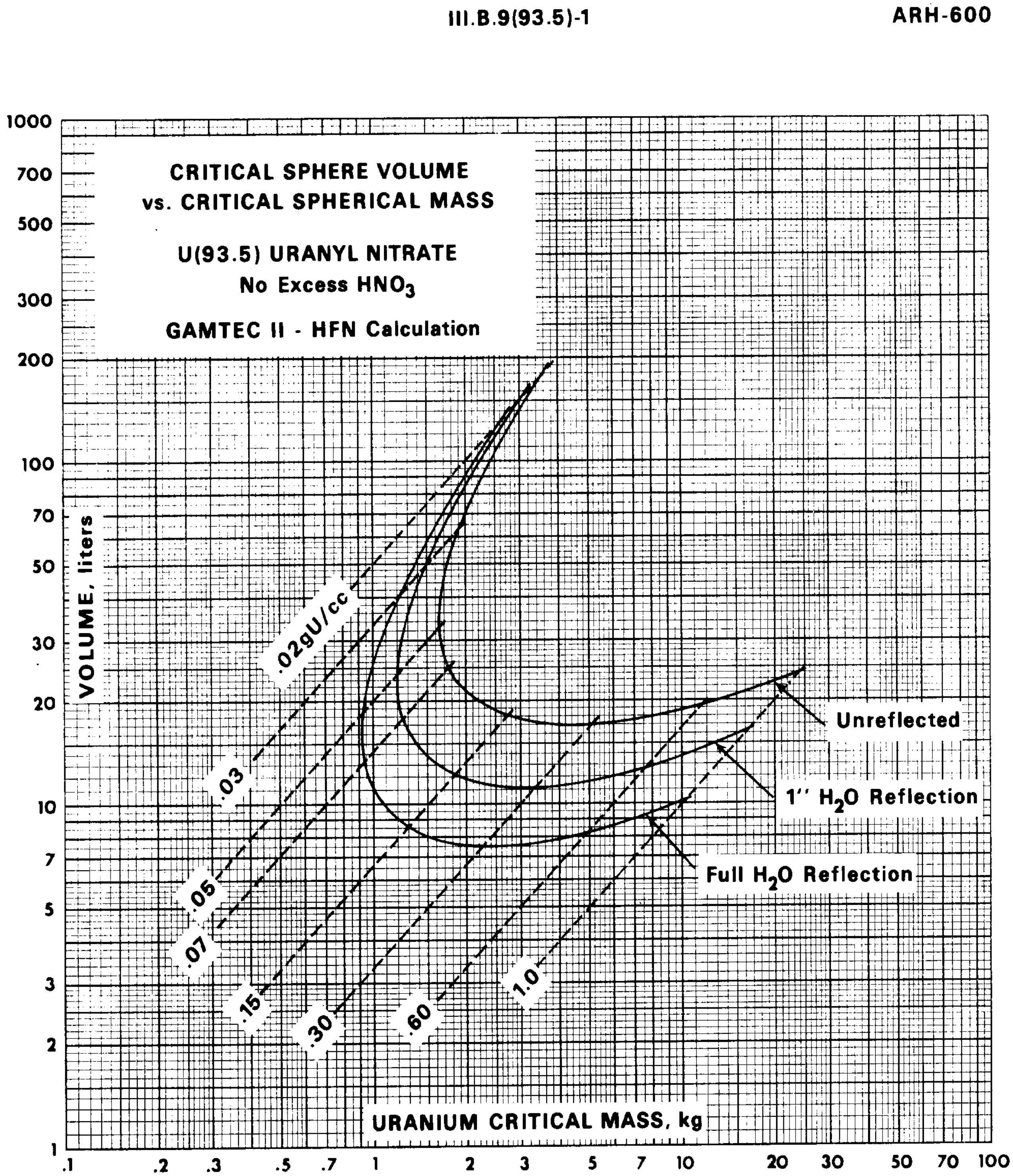

Figure 9 HEU $UO_2(NO_3)_2$–H_2O critical sphere volume (L) vs uranium mass (kg)

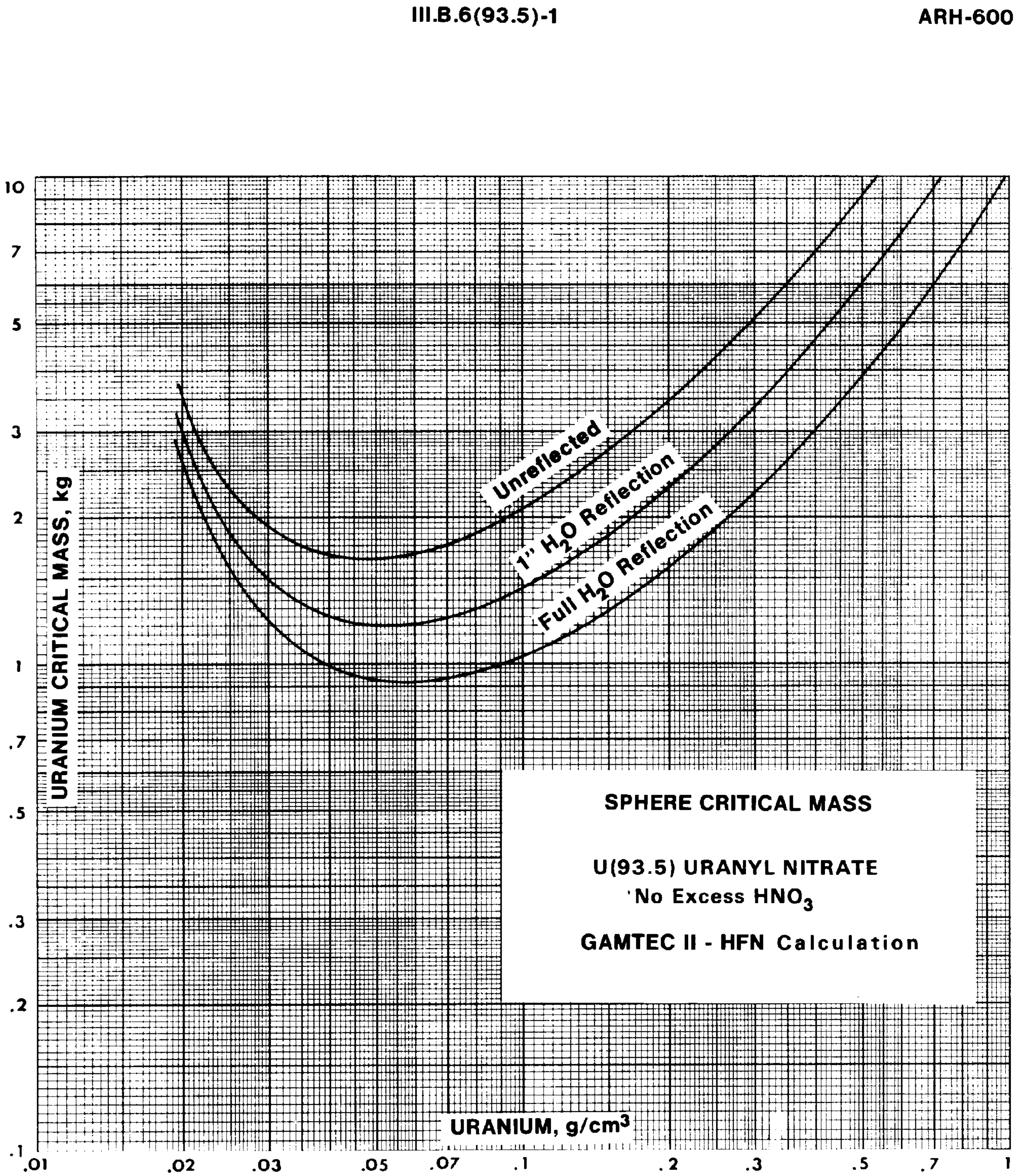

Figure 10 HEU $UO_2(NO_3)_2$–H_2O critical sphere uranium mass (kg) vs uranium density (g/cm^3)

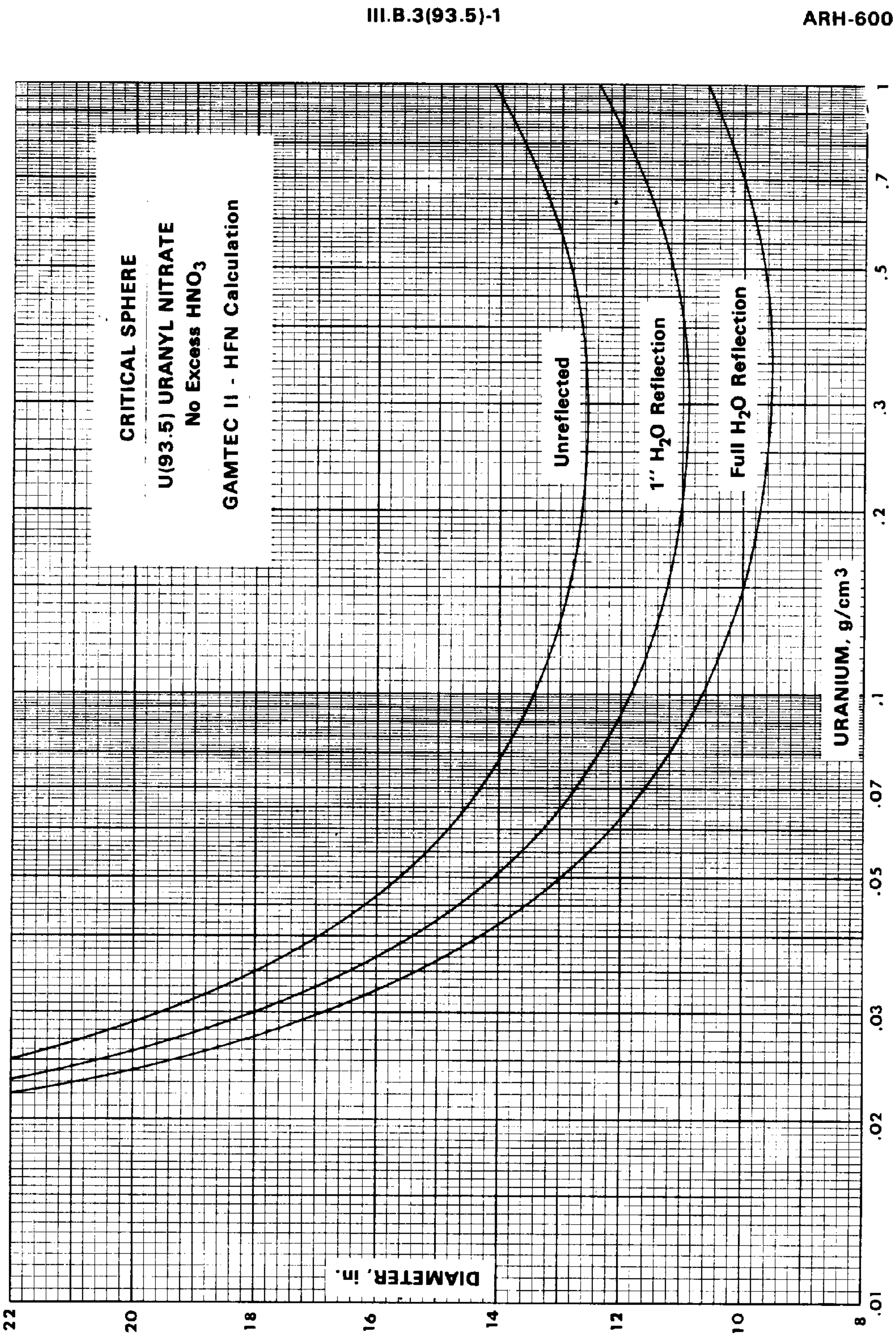

Figure 11 HEU $UO_2(NO_3)_2$–H_2O critical sphere diameter (in.) vs uranium density (g/cm^3)

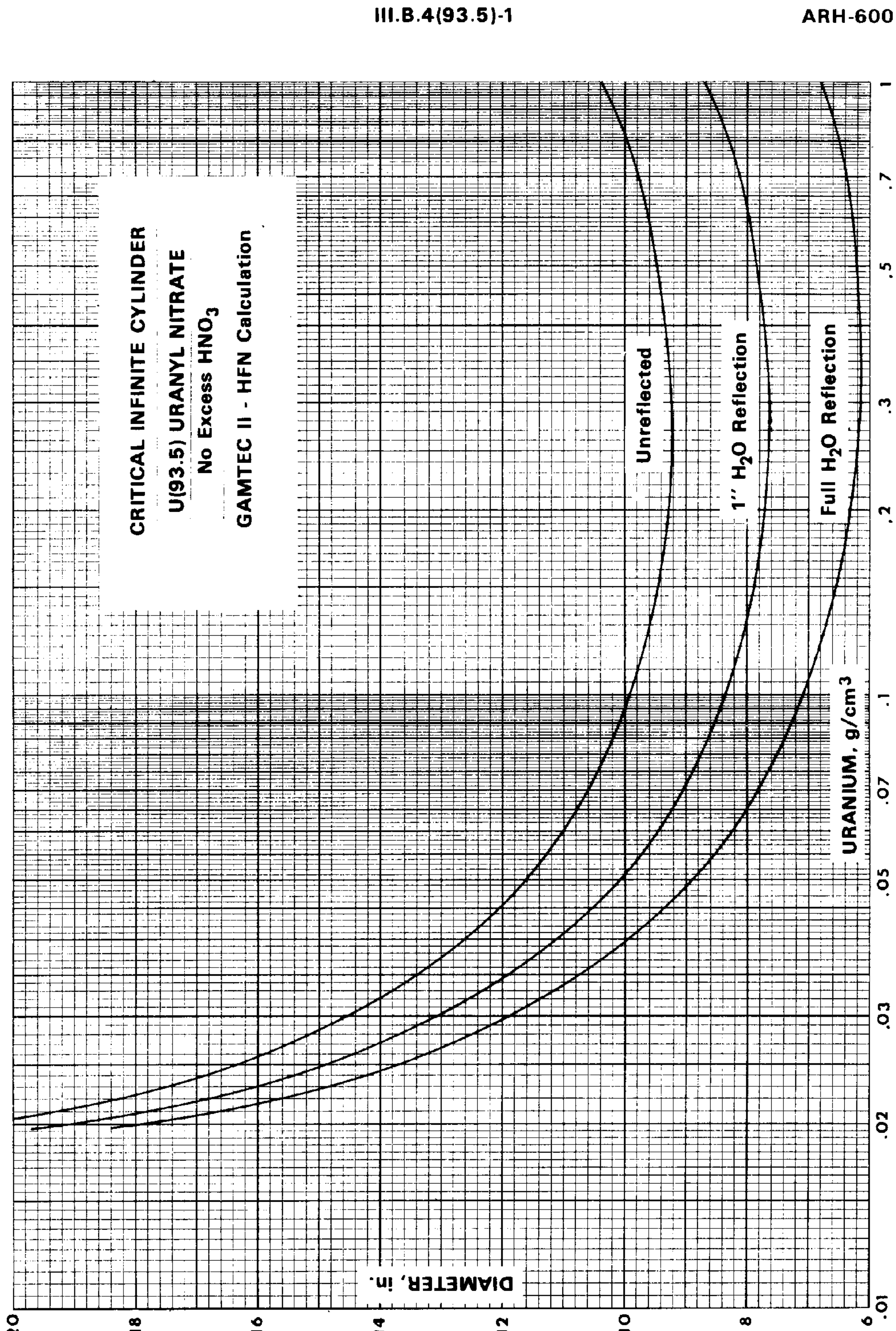

Figure 12 HEU $UO_2(NO_3)_2$–H_2O critical infinite cylinder diameter (in.) vs uranium density (g/cm^3)

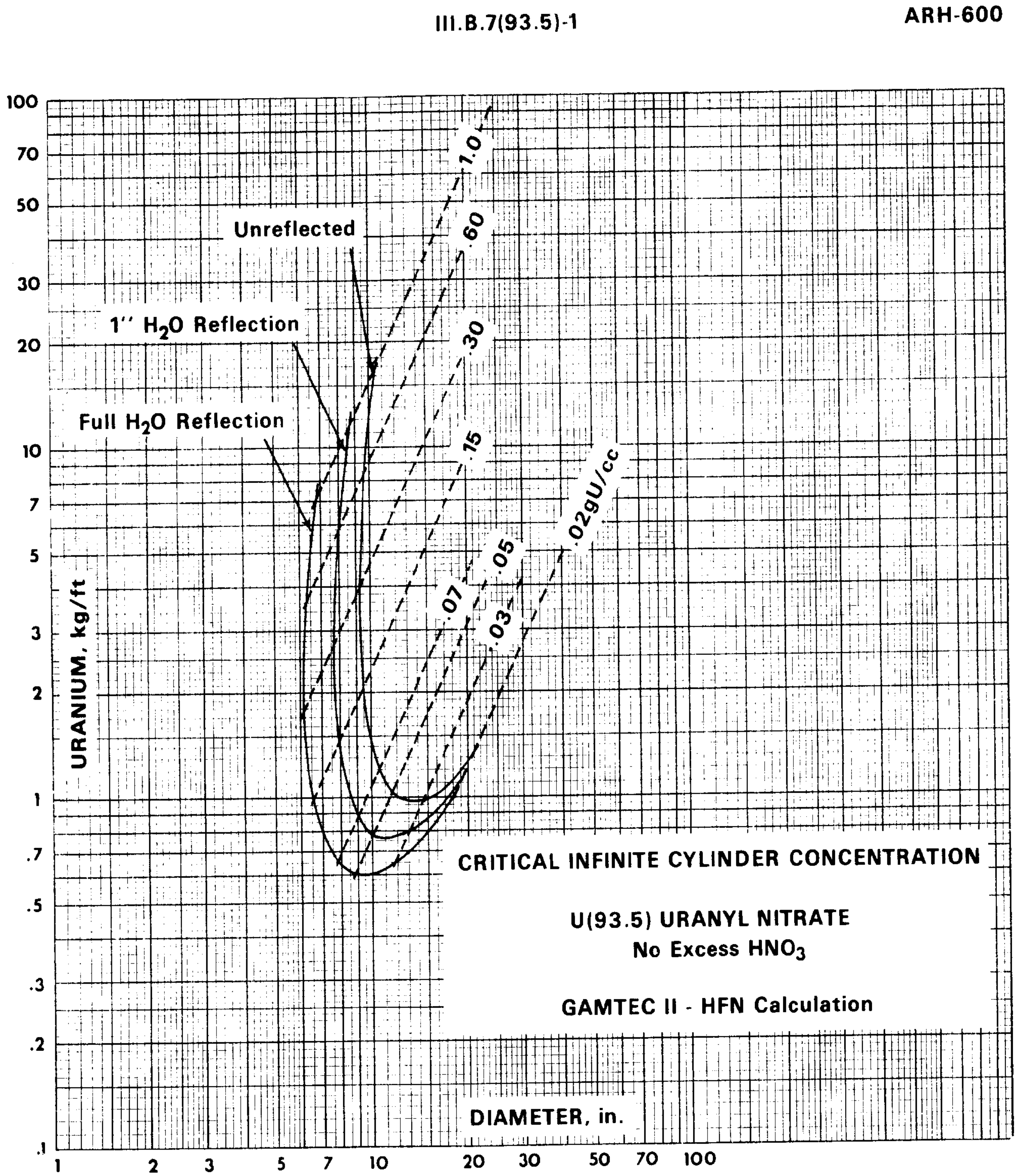

Figure 13 HEU $UO_2(NO_3)_2$–H_2O critical cylinder uranium linear density (kg/ft) vs diameter (in.)

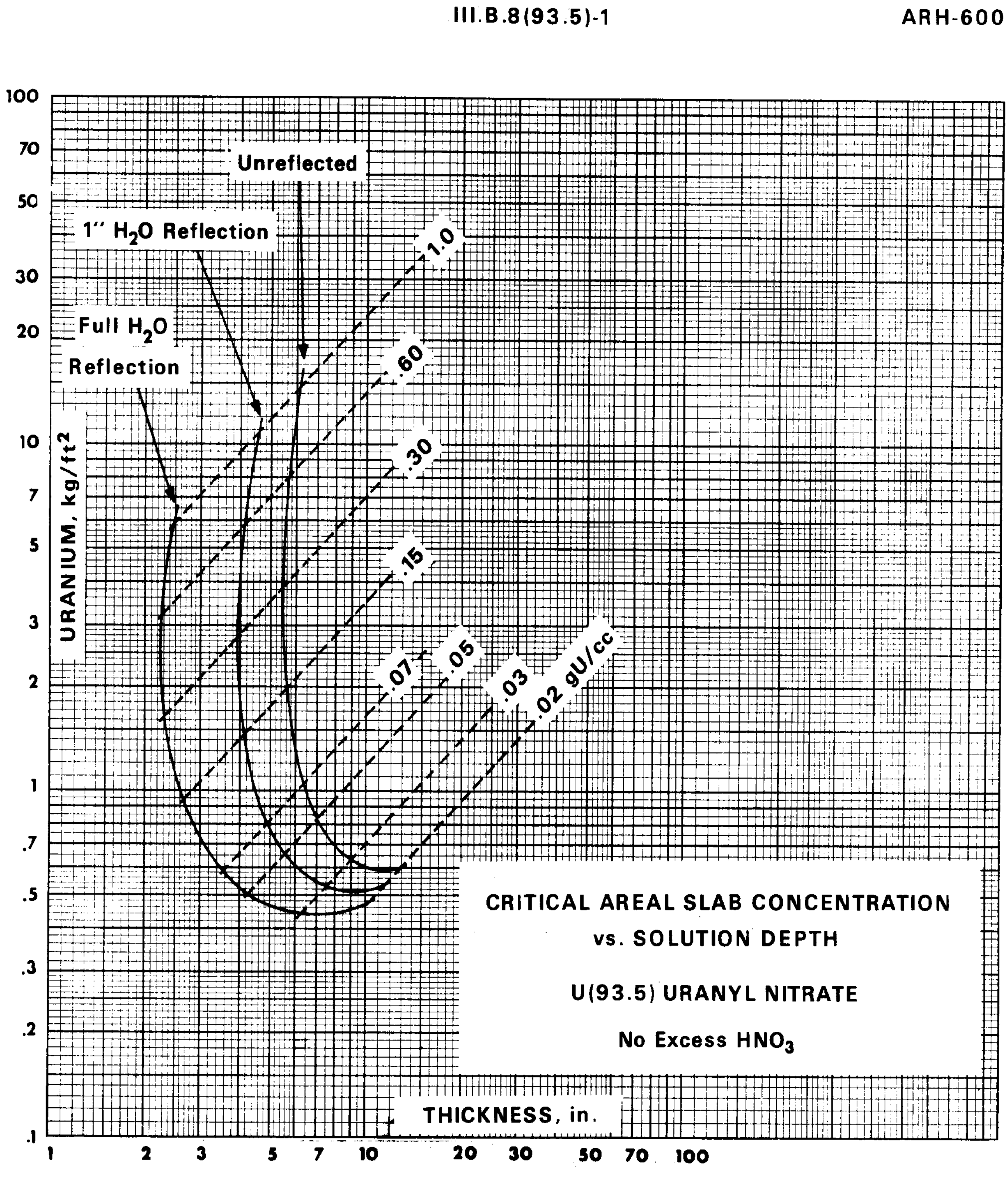

Figure 14 HEU $UO_2(NO_3)_2$–H_2O critical slab uranium areal density (kg/ft^2) vs thickness (in.)

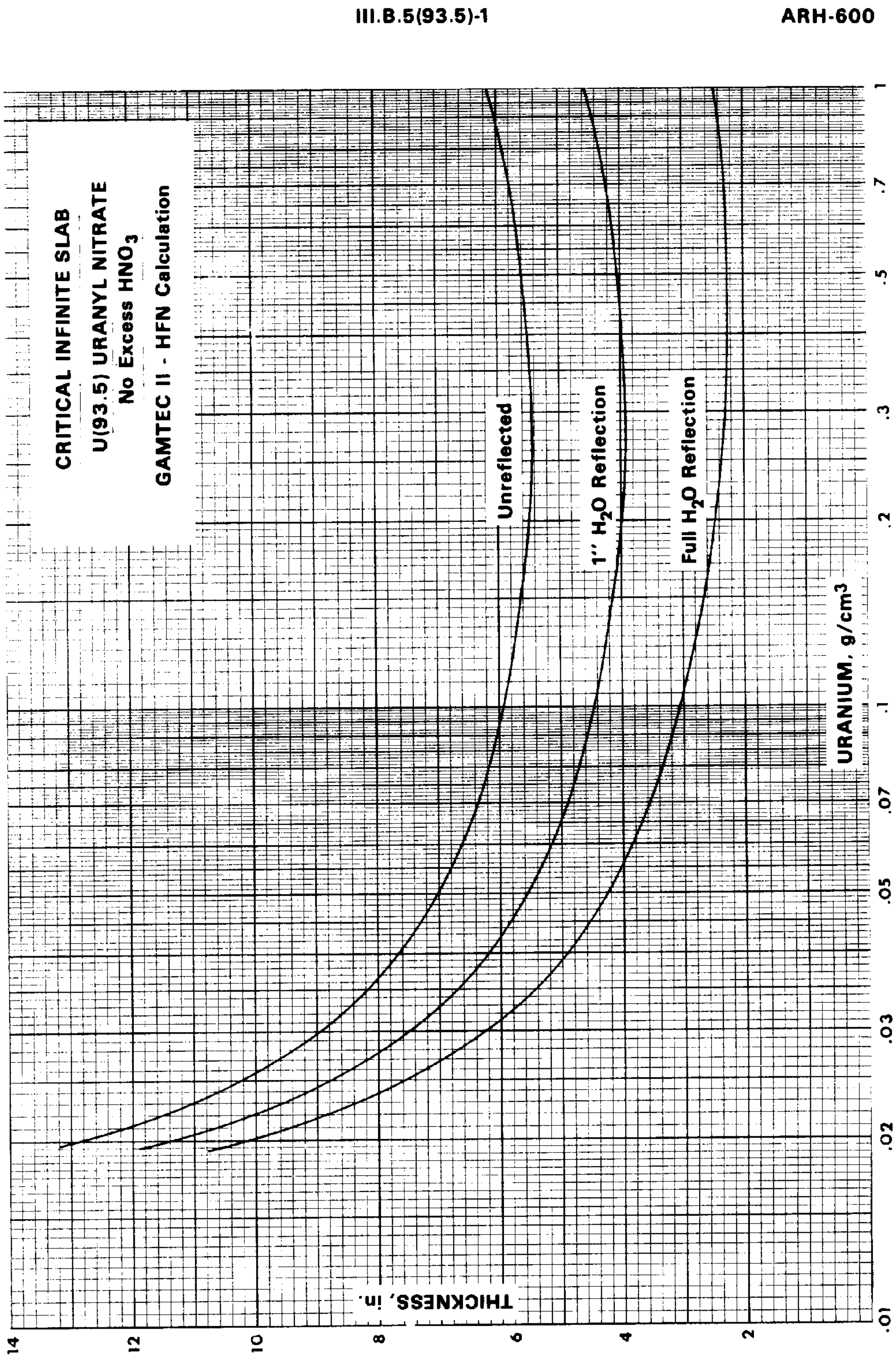

Figure 15 HEU $UO_2(NO_3)_2$–H_2O critical slab thickness (in.) vs uranium density (g/cm^3)

3 SUMMARY/CONCLUSIONS

This slide rule is a functional update to the original slide rule published in limited form in the early 1970s. The general format and features of the original slide rule are retained, in that the various curves include a prompt-dose-vs-distance relationship, a fission-product, gamma-dose-rate-vs-distance-and-time relationship, a total-dose-vs-time-and-distance relationship, and a 1-min total-dose-vs-time-and-distance relationship. The original slide rule consisted of only two system types — highly enriched uranium solutions and metal — and contained a number of approximations, namely an assumed inverse-square relationship of neutron and gamma-ray doses with distance. The newly updated slide rule contains information for the following five systems:

1. unreflected sphere of 4.95 wt % enriched aqueous uranyl fluoride, $U(4.95)O_2F_2{\cdot}H_2O$, solution having a hydrogen-to-^{235}U ratio of 410 (solution density = 2.16 g/cm^3),

2. unreflected sphere of damp 5 wt % enriched uranium dioxide, $U(5)O_2$ having a hydrogen-to-^{235}U ratio of 200,

3. unreflected sphere of 93.2 wt % enriched uranyl nitrate, $U(93.2)O_2(NO_3)_2{\cdot}6H2O$, solution having a hydrogen-to-^{235}U atom ratio of 500 (solution density = 1.075 g/cm^3),

4. unreflected sphere of 93.2 wt % enriched uranium metal sphere (metal density = 18.85 g/cm^3), and

5. unreflected sphere of damp 93.2 wt % enriched uranium oxide, U_3O_8 plus water, having a hydrogen-to-^{235}U atom ratio of 10 (uranium oxide density = 4.15 g/cm^3).

This update also includes not only the air/ground interface effects near the assumed accident, but out to 4000 ft (1219.2 m) as well. The possibility of a shielded criticality accident in which skyshine radiation can be important is also treated, with the inclusion of a separate skyshine contribution as a function of distance from the accident. Also, results of first-pulse, fission-yield estimate evaluations are presented as functions of vertical or horizontal cylindrical critical volumes (based upon the degree of fissile material moderation expressed in terms of uranium density and cylinder dimension) and material addition rates. The first-pulse, fission-yield estimates may then be used for determining appropriate mitigating measures for protection of personnel as an uncontrolled system approaches criticality.

Though the presentation of dose and dose-rate information for less than 1 min (i.e., 1 to 60 s elapsed time) following the initial or prompt fission yield has no use for an emergency response, the information is useful for emergency preparedness in the training of personnel to respond quickly to a criticality accident alarm or in the estimation of radiation fields at the time of the accident, or very shortly thereafter.

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5 APPENDIX

CONTENTS

Slide 1 Solution of $U(93.2)O_2(NO_3)_2$ @ $H/^{235}U = 500$

Slide 2 U(93.2) metal

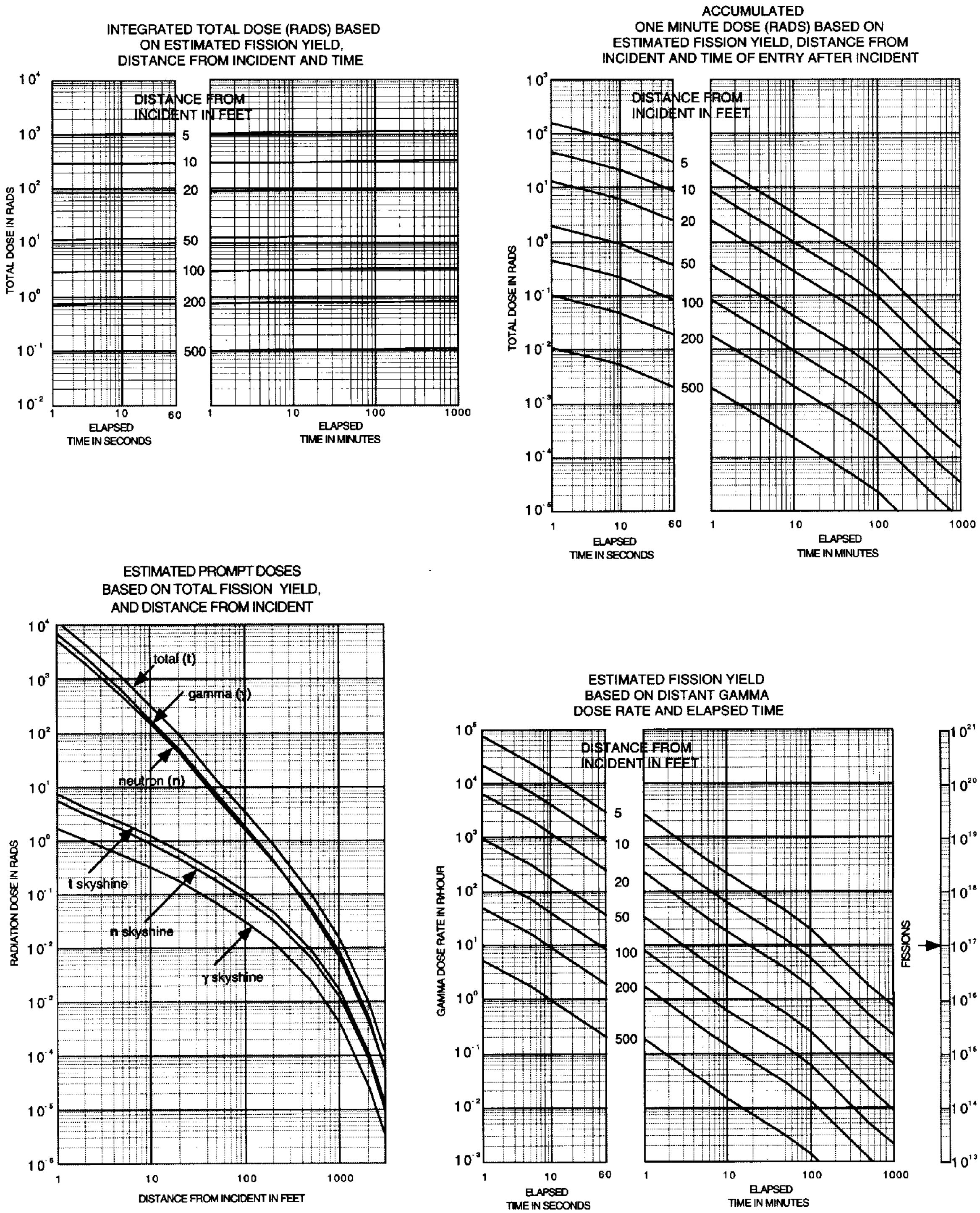
Slide 3 Damp $U(93.2)_3O_8$ @ $H/^{235}U = 10$

Slide 4 Damp $U(4.95)O_2F_2$ @ $H/^{235}U = 410$

Slide 5 Damp $U(5)O_2$ @ $H/^{235}U = 200$

Slide 6 First-pulse, fission-yield estimates for vertical and horizontal cylinders of HEU and LEU solutions

CONVERSION FACTORS AND EQUALITIES



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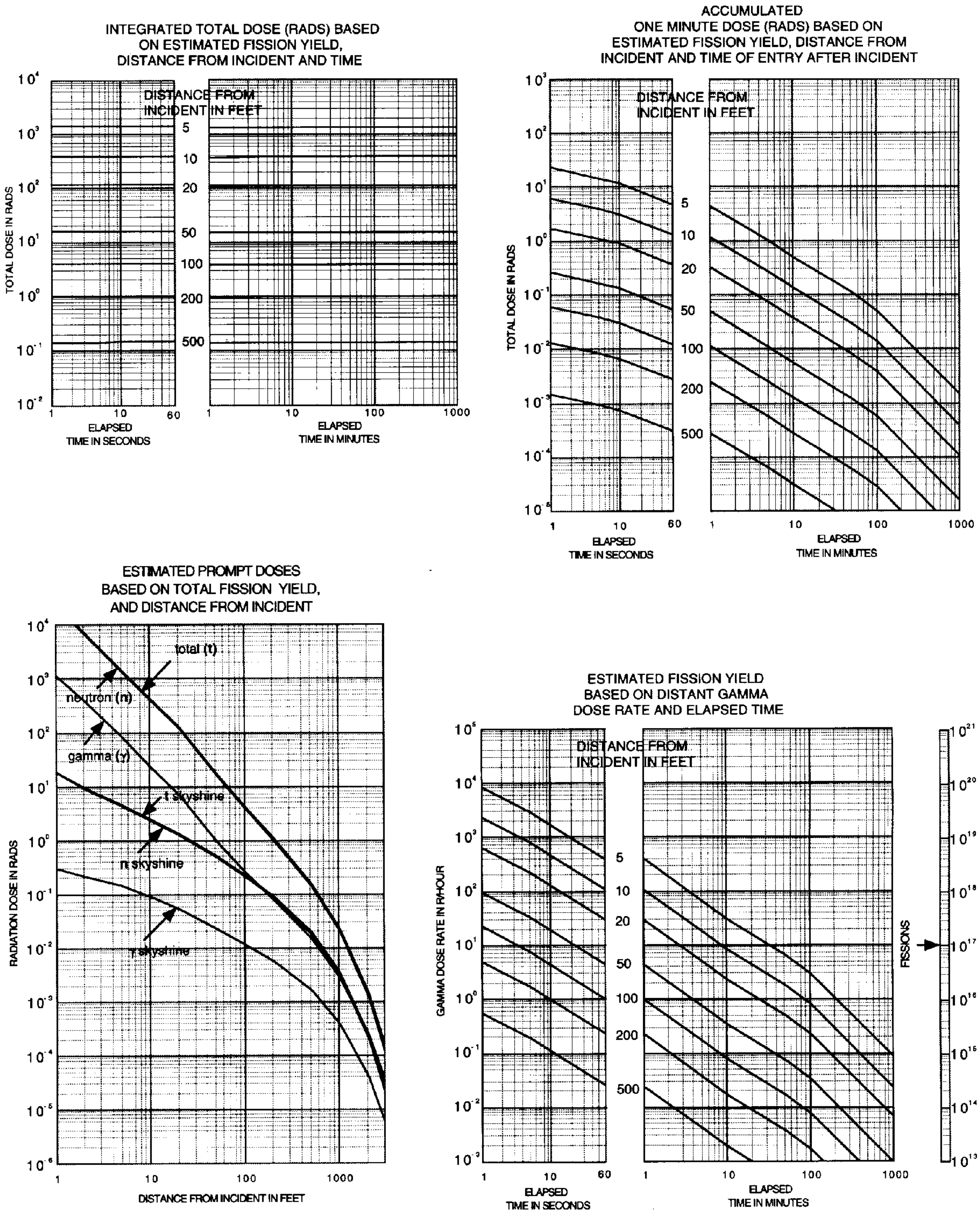

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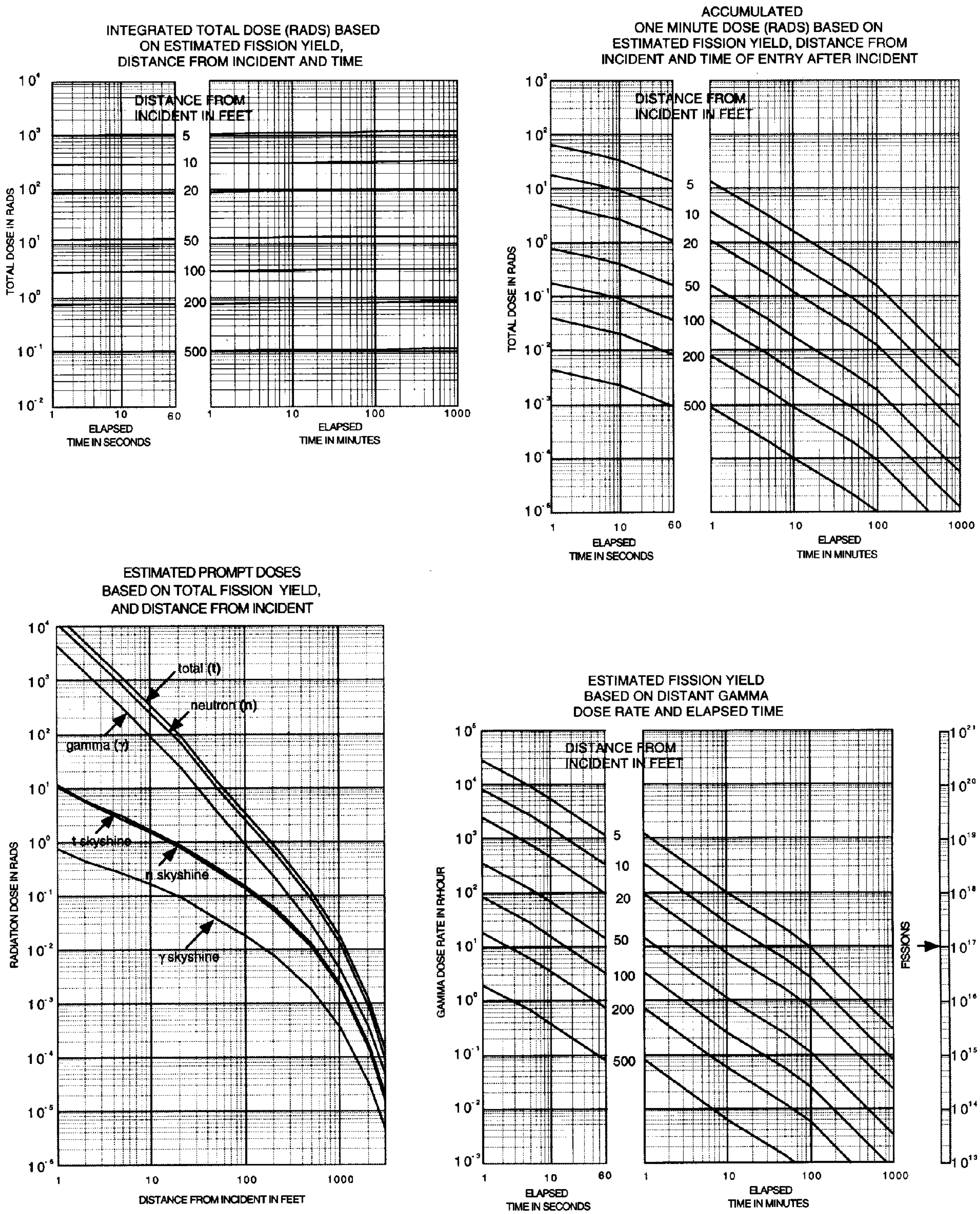
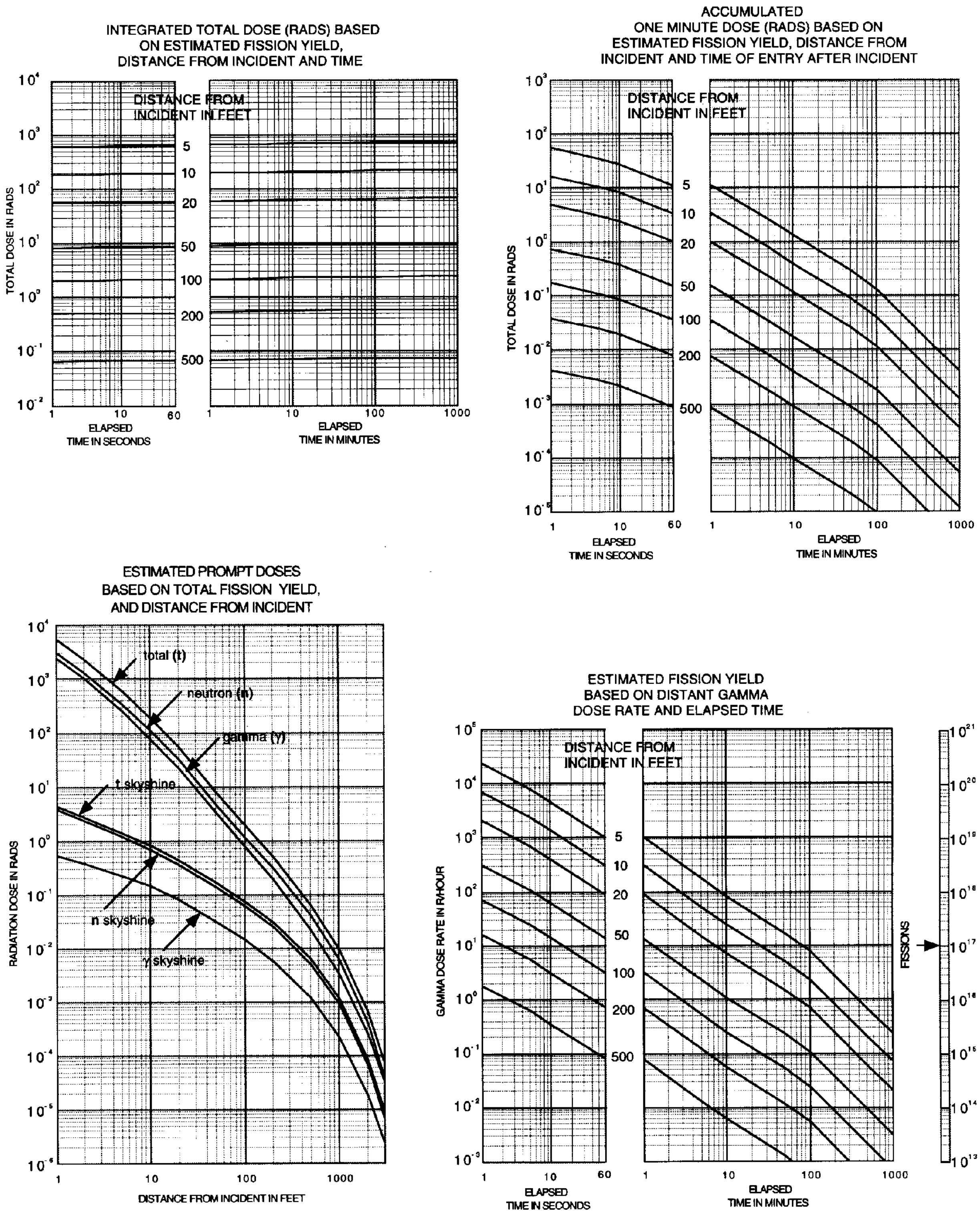
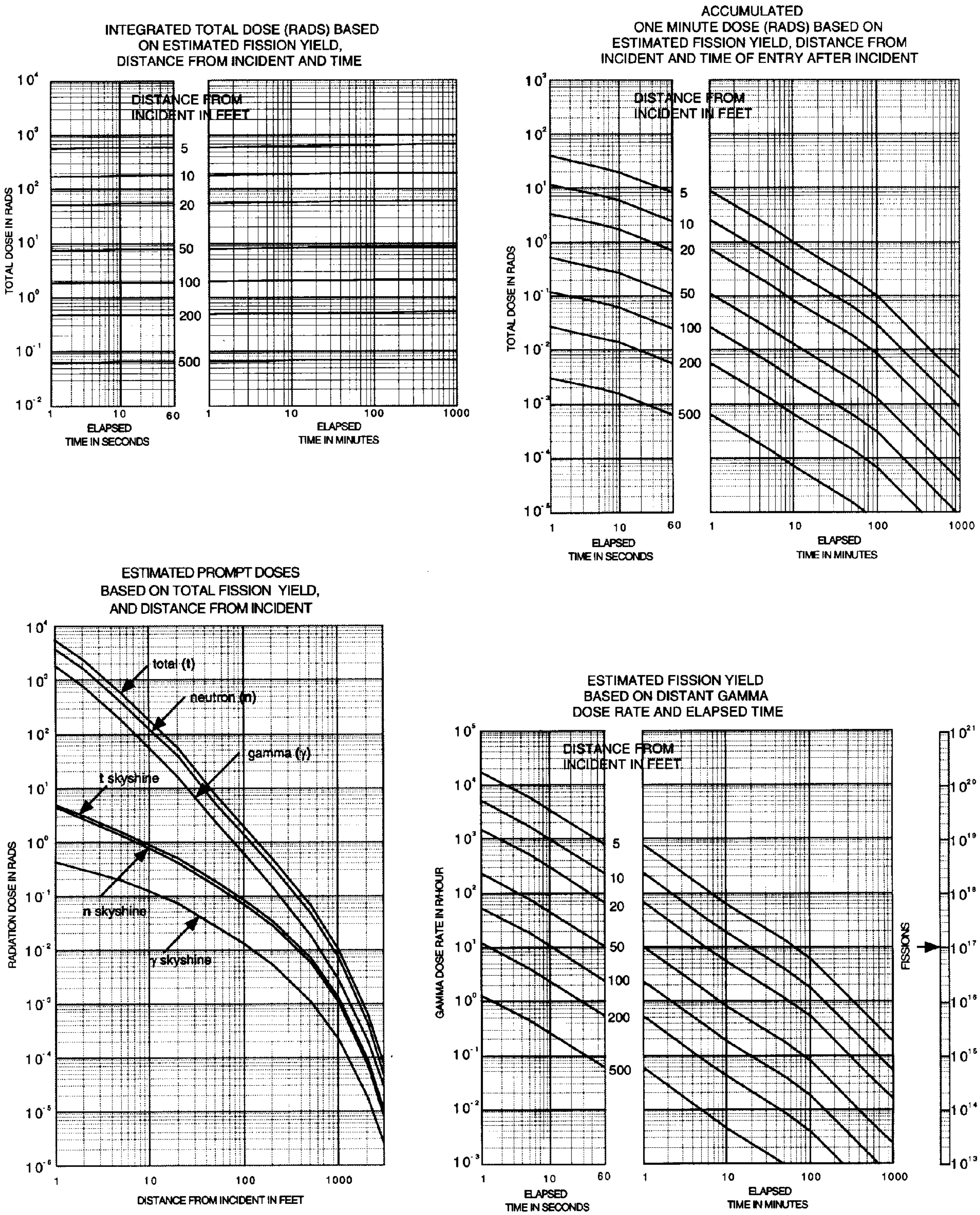


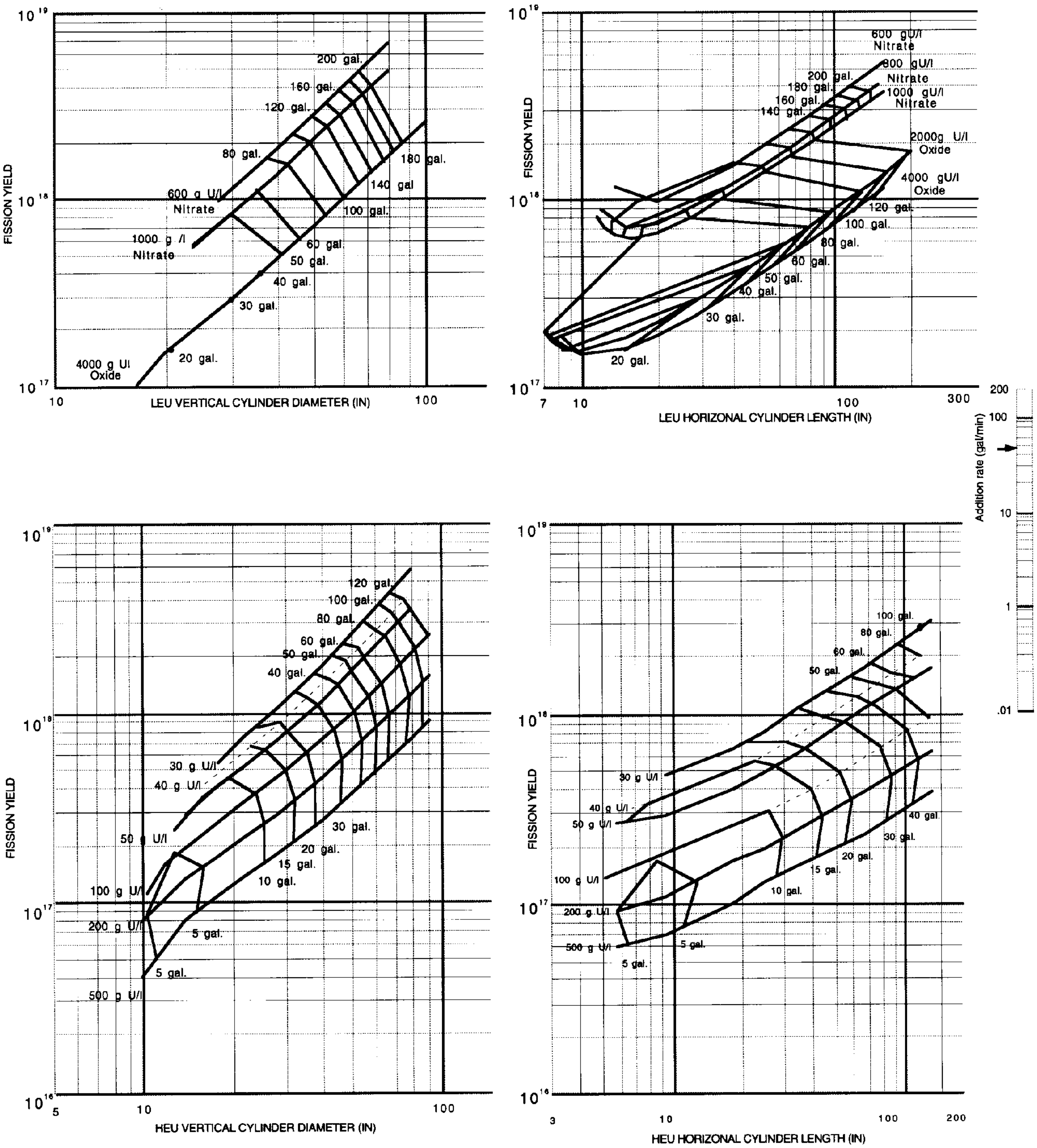
Slide 3 Damp $U(93.2)_3O_8$ @ $H/^{235}U = 10$



Slide 4 Damp $U(4.95)O_2F_2$ @ $H/^{235}U = 410$



Slide 5 Damp $U(5)O_2$ @ $H/^{235}U = 200$



Slide 6 First-pulse, fission-yield estimates for vertical and horizontal cylinders of HEU and LEU solutions

CONVERSION FACTORS AND EQUALITIES

It requires approximately 10^{17} fissions to evaporate 1 L of water that was originally at room temperature.

It requires approximately 3.8×10^{17} fissions to evaporate 1 gal of water that was originally at room temperature.

3.12×10^{10} fissions per seconds (s) = 1 watt (w)

1.123×10^{14} fissions = 1 w-hr

1 gal = 3.785 L

1 liter (L) = 0.264 gal

1 liter (L) / min = 0.264 gal / min

1 cubic foot (ft^3) = 7.481 gal

1 cm = 0.394 in.

The total fission yield[3] of a continuing aqueous solution criticality may be estimated by:

$$\text{Total Fissions} = \frac{[(\text{Solution volume, gal}) \times (\text{Duration of criticality, min})]}{1.563 \times 10^{-17} + [1.686 \times 10^{-17} \times (\text{Duration of criticality, min})]}$$

$$= \frac{[(\_\_\_\_\_\text{, gal}) \times (\_\_\_\_\_\text{, min})] \text{ fissions}}{1.563 \times 10^{-17} + [1.686 \times 10^{-17} \times (\_\_\_\_\_\text{, min})]} = \_\_\_\_\_\_\_\_\_ \text{ fissions}$$

or

$$= \frac{[(\_\_\_\_\_\text{, L}) \times (\_\_\_\_\_\text{, s})] \text{ fissions}}{3.55 \times 10^{-15} + [6.38 \times 10^{-17} \times (\_\_\_\_\_\text{, s})]} = \_\_\_\_\_\_\_\_\_ \text{ fissions.}$$

Shielding dose reduction factors may be determined from the following relationships:

Steel Dose Reduction Factor:	neutrons, $n = e^{-0.256 \times \text{steel thickness in inches}}$ gammas, $\gamma = e^{-0.386 \times \text{steel thickness in inches}}$
Concrete Dose Reduction Factor:	neutrons, $n = e^{-0.240 \times \text{concrete thickness in inches}}$ gammas, $\gamma = e^{-0.147 \times \text{concrete thickness in inches}}$
Water Dose Reduction Factor:	neutrons, $n = e^{-0.277 \times \text{water thickness in inches}}$ gammas, $\gamma = e^{-0.092 \times \text{water thickness in inches}}$

Solution of $U(93.2)O_2(NO_3)_2$ @ $H/^{235}U = 500$
2. U(93.2) metal
3. Damp $U(93.2)_3O_8$ @ $H/^{235}U = 10$
4. Damp $U(4.95)O_2F_2$ @ $H/^{235}U = 410$
5. Damp $U(5)O_2$ @ $H/^{235}U = 200$

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10. SUPPLEMENTARY NOTES

M. L. Thomas, NRC Project Manager

11. ABSTRACT *(200 words or less)*

This Volume 2 contains the functional version of the updated nuclear criticality slide rule (more accurately, sliding graphs) that is referenced in *An Updated Nuclear Criticality Slide Rule: Technical Basis*, NUREG/CR-6504, Vol. 1 (ORNL/TM-13322/V1). This functional slide rule provides a readily usable "in-hand" method for estimating pertinent nuclear criticality accident information from sliding graphs, thereby permitting (1) the rapid estimation of pertinent criticality accident information without laborious or sophisticated calculations in a nuclear criticality emergency situation, (2) the appraisal of potential fission yields and external personnel radiation exposures for facility safety analyses, and (3) a technical basis for emergency preparedness and training programs at nonreactor nuclear facilities. The slide rule permits the estimation of neutron and gamma dose rates and integrated doses based upon estimated fission yields, distance from the fission source, and time-after criticality accidents for five different critical systems. Another sliding graph permits the estimation of critical solution fission yields based upon fissile material concentration, critical vessel geometry, and solution addition rate. Another graph provides neutron and gamma dose-reduction factors for water, steel, and concrete. Graphs from historic documents are provided as references for estimating critical parameters of various fissile material systems. Conversion factors for various English and metric units are provided for quick reference.

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